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MODELLING VOLATILITY OF FINANCIAL TIME SERIES WITH THE HELP OF MULTIDIMENSIONAL GARCH AND HAR MODELS

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Motivation

Volatility is an important financial indicator in financial markets. Usually, volatility is understood as a value that describes the variability of an asset price. Volatility is of great interest to investors in terms of assessing the risks of investing in a particular market or asset. Although volatility cannot be calculated directly, there are many different models developed over the past forty years to describe its properties and predict volatility, as well as many scientific articles have been devoted to the study of the properties of these models (Aganin, 2017). For a long time, the most popular volatility models are those of the GARCH family. A feature of this family of models is that they consider volatility as an unobservable value. The GARCH models are also able to model some important empirical volatility features, such as volatility clustering and long memory, which explains their popularity. In addition to the GARCH family of models, the literature suggests using other families, such as ARFIMA, MIDAS, the Heston model, and others.

Realized volatility (RV) is widely used in the literature and in practice as an observable approximation of volatility, which has become widely used with the advent of high-frequency intraday price quotation data. This is due to the fact that realized volatility is a consistent assessment of unobservable volatility. The HAR-RV models proposed in Corsi (2009) developed the idea of modeling realized volatility. Later, there were many articles with various modifications of the basic HAR-RV model, as well as comparison of some models of this family with single representatives of already-existing families of volatility models based on their out-of-sample forecast power.

In the literature, model comparisons for out-of-sample volatility forecasting demonstrate the superiority of HAR-RV models over individual representatives of other families. It is worth noting that comparing the volatility models in terms of the quality of out-of-sample volatility forecasting is preferable

to comparing the quality of in-sample volatility estimation. This is due to the fact that the conclusions about the superiority of certain models obtained during in-sample comparison using the same data can differ significantly from the conclusion of a similar comparison using new data. Comparisons in which models are compared by forecasting future volatility that the models have not yet observed are considered more informative and correct. Such comparisons will not give preference to models that suffer from excessive fitting of in-sample data to models with a large number of parameters.

After popularization of the HAR-RV family of models, interest in realized volatility increased and the use of RV estimates went beyond this model family. For example, one of the recent trends in modeling and forecasting volatility is related to the modeling of "rough" volatility, which appeared after the publication of the article (Gatheral et al., 2014). Since a wide comparison of the GARCH and HAR-RV model families has not been made, there may be doubts when choosing a family of volatility models. Is it worth modeling volatility using GARCH models or is it better to use HAR-RV models? In this regard, it seems interesting to perform such a comparison, in particular, on Russian stock quotes.

A popular subject of volatility research is the detection of volatility "spillover" effects from one market to another. Such studies are devoted to the relationship between the volatility of commodity markets, stock markets, and macro indicators of various countries. Multi-dimensional BEKK-GARCH and DCC models that do not use intraday quotes are very popular for detecting the spillover effect. This is due to both the lack of the need to use intraday data and the lack of development of new directions for modeling such effects. These models are used to determine whether there is a significant volatility spillover effect or to forecast volatility, but they are not suitable for most more complex tasks.

For example, what if we are interested not in determining the presence of the spillover effect itself, but in studying the influence of various factors on the

volatility of the indicator, including volatility in other markets? Theoretically, the logical step would be to include such factors in the BEKK-GARCH equation of the model. However, BEKK-GARCH models already contain a large number of parameters that are difficult to estimate using numerical methods. Parameter estimates can change significantly with a small increase/decrease in the time interval, and the evaluation itself takes a long time due to the need to use multiple starting sets of parameters. Due to the difficulties in evaluating BEKK-GARCH models, researchers have begun to use DCC models that do not have this problem more often. If we talk about DCC models, their properties have not yet been well studied and, in particular, the conditions for the optimality of numerical estimation of the parameters of these models have not been determined, so the results of their evaluation and interpretation may be unreliable. Adding more parameters to the model complicates the evaluation of models even more and may lead to inadequate results. Another problem is that the results of evaluating multi-dimensional volatility models cannot be interpreted. Since the volatility dynamics in these models is represented as a product of matrices, it is not possible to quantify the influence of exogenous factors on the dependent variable. Thus, the traditional approach of multi-dimensional models is not suitable for evaluating the quantitative and qualitative effects of exogenous factors.

Degree of Problem Elaboration

This thesis aims to assess the impact of oil price volatility, sanctions imposed against the Russian Federation since 2014 and other macroeconomic indicators on the volatility of the dollar/ruble exchange rate and the volatility of the Russian stock market. It is worth noting that the very fact of the spillover effect of oil price volatility into the Russian stock market is well studied in the literature using BEKK models. However, since 2014, in connection with the crisis in Ukraine and the subsequent introduction of sanctions against the Russian Federation, the impact of oil volatility and sanctions should be modeled together.

This is not possible in the framework of traditionally used volatility spillover models due to the need to include additional parameters, which leads to inadequate and unreliable results of evaluating these models using numerical methods.

In the literature, a number of articles are devoted to the detection of both the effect of oil price influence on the stock indices of oil-exporting and -importing countries, and the effect of oil price volatility influence on the volatility of stock indices of these countries. For example, the paper (Basher et al., 2018) revealed a significant effect of oil supply/demand shocks on the stock markets of oil-exporting countries, although the impact varies by country. Wang et al. (2018) showed an improvement in the quality of short-term returns volatility forecasts of the S&P 500 US stock index when including oil price volatility in the model.

Gomes and Chaibi (2014) analyzed the presence of effects of shock transmission and volatility between the stock markets of twenty-three underdeveloped countries and the oil price using the BEKK-GARCH model. It was found that there is an oil volatility transmission effect on the stock markets of some of these countries. It is worth highlighting the paper (Degiannakis et al., 2018), which summarizes the results of many studies on these issues based on data from developing and developed countries of the world. The authors conclude that there is a significant influence of oil prices on the stock indexes of oil-exporting countries and a similar influence for the volatility of these indicators. The reverse effect was found only for the US stock market. It is shown that an increase in the oil price leads to negative returns on the indices of importing countries, and a fall in the oil price – to negative returns on the indices of exporting countries.

There are several similar studies about the Russian Federation, since it is one of the largest oil exporters in the world, and oil is an important component of the Russian economy. Exports of oil and petroleum products amounted to 45.8% of Russia's total exports in 2018 according to the Federal Customs Service of

Russia. For example, the paper (Živkov et al., 2018) analyzed the presence of a volatility spillover effect between the commodity market (including oil) and the RTSI index for the period 2001-2016. Based on the results obtained, the authors also concluded that this effect increases during crisis periods and decreases during calm periods. In the paper (Lozinskaia, Saltykova, 2019), the authors found the variability of the influence of oil prices and other macroeconomic factors on the Moscow Exchange (MOEX) index in the interval 2003-2018. According to the results (Izatov A., 2015), the growth of oil prices and the devaluation of the national currency significantly affected economic activity in the Russian Federation in the period 1995-2015.

Soon after the introduction of sanctions by the United States and Europe against Russia in 2014, research papers analyzing the impact of sanctions on certain sectors of the country's economy, as well as its macroeconomic indicators, using the Russian Federation as an example, began to appear. Since the reaction to such events is usually instantaneous in financial markets and accompanied by a sharp increase in volatility, direct changes in the economy should not be considered as the cause of such reaction. But the actions of investors who sharply change their expectations about the current and future value of assets and the riskiness of investing in certain companies after receiving new information about the introduction of sanctions and other events should be responsible. Talking about the impact of sanctions on the Russian economy, we can distinguish the following papers. Kholodilin, Netšunajev (2019) analyzed the impact of oil and sanctions on the Russian and European economies based on quarterly data for 1997-2015. The authors found a significant negative impact of sanctions on the growth rate of the Russian GDP. Tuzova and Qayub (2016), after analyzing the impact of oil prices and sanctions, concluded that the sharp fall in oil prices in 2014 was the main reason for the fall in Russia's macroeconomic indicators.

Since the introduction of sanctions led to an outflow of foreign investment from Russia, this should have had an impact on the entire stock market. For

example, in the paper (Rubtsov, Annenskaya, 2018), the authors analyze the factors influencing the stock market of the Russian Federation for 2000-2017, and conclude that the greatest impact on the stock market from 2014 to 2017 was exerted by sanctions. In the paper (Ahn, Ludema, 2019), the authors analyzed the impact of individual sanctions aimed at specific companies on the example of the Russian Federation for the period 2012-2016. They came to the conclusion that individual sanctions have proved to be effective against specific companies compared to the companies against which no sanctions were imposed. Naidenova and Novikova (2018), having analyzed the impact of 2014-2016 sanctions, found that the effect of individual US sanctions on Russian companies whose shares are traded on the Russian stock market was stronger than the effect of individual European sanctions.

Since the Russian Federation is still subject to sanctions in 2020, the issue of their impact remains relevant. It is worth noting that the research found by the author massively considered the period before 2016, after which the interest in analyzing the impact of sanctions significantly decreased, although new sanctions were introduced after that. To assess the effect of sanctions in the context of volatility, it is first necessary to evaluate the volatility of the Russian stock market, the USD/RUB exchange rate, and the volatility of oil prices, and then model the type of relationship between these volatilities.

Since the problem of volatility modeling occupies an important place in this thesis, first various approaches to volatility modeling and the corresponding families of models should be investigated. It is logical to compare volatility models on Russian stock quotes and use the best approach or best models. In the literature, comparison of families of volatility models is often represented by comparisons of a small set of individual representatives. For example, Mastro (2014) found that the simplest HAR-RV model is superior to the GARCH (1.1) and EGARCH (1.1) models. However, the comparison of a great number of models from different families on a large data set to identify statistically

significant superiority of some models over others was not performed. Similar studies were also not performed using data from Russian stock assets.

Object and Subject of Research

The object of the thesis research is the volatility of the stock market and the USD/RUB exchange rate as indicators of the state of the Russian economy. The subject of the research is the applicability of approaches to modeling and forecasting volatility based on Russian stock market data, as well as the impact of sanctions and oil volatility on stock market and exchange rate volatility. Attention was paid to the Russian stock market, since it demonstrates investors' expectations regarding the impact of current oil prices and sanctions aimed at both entire sectors of the Russian economy and individual companies in the Russian economy. The impact of oil and sanctions on the volatility of the USD/RUB exchange rate was also analyzed, which showed a significant drop in the post-sanction period.

Research goal and objectives

The purpose of the research is modeling and assessing volatility of the main assets of the Russian stock market, as well as searching for factors that affect the volatility of the USD/RUB exchange rate and the RTS stock index. Objectives include:

- to formulate specifications of one-dimensional GARCH, HAR and ARFIMA models as approaches to volatility modeling;
- to implement assessment procedures for these models;
- to compare these approaches to volatility modeling;
- to evaluate the volatility of the USD/RUB exchange rate, Brent oil prices, and the RTSI stock index using parametric and nonparametric approaches;
- to identify a set of potential factors that affect RTSI and USD/RUB volatility, such as Central Bank sanctions and policies;

• to simulate the impact of sanctions;

• to analyze the possibility of applying multi-dimensional volatility models, as well as standard regression methods to assess the impact of selected factors;

• to create appropriate models and draw conclusions about the presence and type of impact of sanctions and oil on the RTSI and USD/RUB volatility.

Research Methods and Data

The thesis uses methods of time series analysis, volatility modeling, and econometric analysis. Models were evaluated using the R programming language for statistical calculations (R CoreTeam, 2020) and the EViews package for statistical calculations.

The purpose of comparing volatility models was to evaluate volatility and compare model forecasting estimates of future volatility with actual future volatility estimates. In total, 88 GARCH models, 10 HAR-RV models, and four ARFIMA models were taken for empirical comparison.

The comparison was based on quotes of ten important Russian exchange-traded assets (Aganin, 2017): shares in ALROSA (ALRS) Diamond Mining Company, shares of Gazprom (GAZP) Power Corporation, NorNickel (GNWK) Mining and Metallurgical Company, LUKOIL (LKOH) Oil Company, MICE (MICEX) composite stock index, MTS (MTSS) Telecommunication Company, Rosneft (ROSN) Oil and Gas Company, Russian Trading System Cash Index (RTSI), the shares of Sberbank of Russia (SBER) and VTB Bank (VTBR) from September 09, 2013 to May 12, 2016, which in total amounts to 654 trading days. The Model Confidence Set (MCS) test proposed in (Hansen et al., 2011) was used to compare models. This test does not require assumptions about the superiority of any model over the others (choice of benchmark), allows for the existence of many models (and not the only one, as in the SPA test) with the same superiority over others, and allows taking into account imperfection of the data used. When

using noisy data, the information available may not be sufficient for the test to determine the only best model. In this case, the test will not detect a significant superiority of the truly best model over some others, and such models will fall into a finite set. Therefore, the quality of the data used to model volatility will determine the size of the finite set of best models, which can be attributed to both the pros and cons of the test.

The objective of modeling and evaluating the impact of sanctions and oil volatility consisted of two stages.

Volatility models were evaluated at the first stage. One-dimensional and two-dimensional GARCH models were used, as well as the implemented volatility approach, which does not require the model specification. The initial data included intraday five-minute quotes of Brent oil prices in US dollars, the values of the USD/RUB exchange rate quotes, and the values of the RTSI stock index quotes, also calculated in US dollars. Data for the period from October 11, 2007 to December 28, 2018 were taken from the website https://www.finam.ru/, where they are provided by the MOEX.

At the second stage, regressions of the logarithm of the RTSI/exchange rate volatility on the logarithm of the oil price volatility were estimated, using model estimates of daily volatility of the RTSI stock index/exchange rate and oil prices, where set of additional macroeconomic factors, such as sanctions, oil price regime, VIX (the volatility index on the US stock market, often used as an indicator of investors' expectations of future market uncertainty), and others was included.

Additionally, regressions in moving windows of 252 observations were evaluated, which corresponds to one trading year. As a result of such estimation, a dynamic dependence of the volatility of Russian macroeconomic indicators on the oil volatility was obtained.

Scientific Novelty

The scientific novelty is as follows:

- the main approaches to volatility modeling based on Russian stock market data are modeled and compared using a large number of assets and models;
- due to the lack of information value of the standard approach for determining the effect of volatility spillover, a two-stage methodology for estimating and modeling the impact of oil price volatility was applied;
- the influence of oil price volatility in dynamics on the volatility of the USD/RUB exchange rate and the RTSI stock index is analyzed;
- the impact of sanctions and other macroeconomic factors on the same volatility was modeled and evaluated;
- all the approaches used showed similar results, which indicates the robustness of the results obtained.

Main findings and contributions

A large number of volatility models based on data from Russian stock assets were compared. The results indicate a clear statistical advantage of HAR-RV models in predicting volatility, however this family of models proved to be unsuitable for further research. At the same time, the implemented volatility approach itself was used as an alternative to model volatility estimation.

- Models have been created to evaluate the oil volatility impact on stock index volatility for oil-exporting countries, including Russia.
- USD/RUB exchange rate and RTS stock index volatility were simulated using parametric and non-parametric approaches.
- An approach to modeling the dynamics of the dependence of these volatilities on the volatility of oil prices is formulated and implemented;
- The effect of sanctions and some other macroeconomic indicators on the volatility of the USD/RUB exchange rate and the volatility of the RTSI stock index was modeled and evaluated;

• A significant positive effect of oil volatility on the exchange rate and the RTSI stock index volatility was found. The effect of the sanctions was not permanent in both cases: it was strongest after the first sanctions were imposed and weakened over time;

• The adaptation of the stock market and the Russian economy to the newly imposed sanctions was found.

Approbation of Research Results

The main conclusions of the thesis research are the result of economic and mathematical modeling. The methods of theoretical and econometric analysis used in this paper correspond to the academic standards accepted in modern scientific literature.

Publications

The main results of the dissertation research are published in the following scientific journals:

1. Aganin A., (2017). Forecast comparison of volatility models on Russian stock market. Applied Econometrics, 48, 63-84 [In Russian].

2. Aganin A., Peresetsky A. (2018). Volatility of ruble exchange rate: Oil and sanctions. Applied Econometrics, vol. 52, pages 5-21 [In Russian].

3. Aganin A. (2020). Russian Stock Index volatility: Oil and sanctions. Voprosy Ekonomiki. 2020(2), pages 86-100 [In Russian].

Conferences

The results of the thesis research were presented at the following international conferences:

1. 8th International Academic Conference for undergraduate, graduate and PhD students «Statistical Methods Application for Analysis of Economics and Society » (Moscow, 2017). Artem Aganin. «Comparison of volatility models on Russian stock data»

2. VI International Youth Research and Practice Conference “Mathematical and Computer Modelling in Economics, Insurance and Risk Management”, Saratov, November 8 – 11, 2017. «Comparison of volatility models on Russian stock data» (with Artem Aganin).

3. 12th International Conference on Computational and Financial Econometrics & 11th International Conference of the ERCIM WG on Computational and Methodological Statistics (Pisa, 2018). «The impact of oil price volatility on the exchange rate in Russia»(with Artem Aganin).

4. Modern Econometric Tools and Applications — META-2018 (Nizhny Novgorod, 2018). Artem Aganin: «Modeling UsdRub volatility with the help of multidimensional volatility models»

5. Scientific workshop «Applied econometrics» as part of XX April International Academic Conference on Economic and Social Development. Artem Aganin: «RTSI volatility: impact of oil price volatility and sanctions»

6. Modern Econometric Tools and Applications — META-2019 (Nizhny Novgorod, 2019). Artem Aganin: «Russian stock market volatility: oil and sanctions»

Structure of the thesis. The dissertation consists of an introduction, three chapters, a conclusion, bibliography and applications. The total amount of work is 123 pages of the main text, as well as 9 figures, 11 tables. The bibliography includes 92 items.